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Revised Baade-Wesselink Analysis of RR Lyrae Stars

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Abstract. We have applied the Baade-Wesselink method to two field RR Lyrae stars, i.e. SW And and RR Cet, and derived their distances and physical parameters. With respect to previous B-W analyses we have applied the following improvements: a) use of all sets of available data, after proper comparison for homogeneity and compatibility; b) use of the most recent and accurate model atmospheres, with turbulent velocity V_{turb} = 4 km/s and the no-overshooting approximation, and comparison with other treatments of convection; c) use of the instantaneous gravity along the pulsation cycle rather than the mean value; d) comparison with modified radial velocity curves according to various assumptions on radial velocity gradients in the atmosphere; and e) careful reanalysis of the temperature scale. The main aim of this study is to evaluate the effect of the above items on the B-W results and verify whether any (or a combination) of them can possibly account for the discrepancy of the absolute magnitude zero-point with respect to other independent determinations.

1. Introduction

The distance scale problem is not solved yet, the dichotomy between *long* and *short* distance scales becoming even more clear-cut. In favour of the *short* distance scale (i.e. faint Mv(RR), $(m - M)_{LMC} \leq 18.3$) are the studies on RR Lyrae statistical parallaxes (Gould & Popowski 1998), local RR Lyrae kinematics (Martin & Morrison 1998), eclipsing binaries in the LMC (Udalski et al. 1998, but see also Guinan et al. 1998 for a contrasting result), red clump stars (Cole 1998), Hipparcos parallaxes of field HB stars (Gratton 1998). On the other hand, in favour of the *long* distance scale (i.e. bright Mv(RR), $(m - M)_{LMC} \geq 18.5$) are the studies on sd-MS fitting in globular clusters (Gratton et al. 1997; Reid 1997; Chaboyer et al. 1998; Pont et al. 1998; Grundahl, VandenBerg, & Andersen 1998; Carretta et al. 1999), RGB bump stars in globular clusters (Ferraro et al. 1999), tip of the RGB (Lee, Freedman & Madore 1993), RR Lyraes period-shift effect (Sandage 1993), RR Lyraes double-mode pulsators (Kovacs & Walker 1998), Hipparcos parallaxes of Cepheids (Feast & Catchpole 1997), SN1987A in the LMC (Panagia 1998).

The Baade-Wesselink (B-W) analysis of RR Lyrae stars can help solve this problem. For a review and general description of this method and its assumptions and approximations see for example Gautschy (1987).

Previous B-W analyses were performed on 29 field RR Lyraes by a few independent groups, e.g. Liu & Janes (1990), Jones et al. (1992), Cacciari, Clementini & Fernley (1992), and Skillen et al. (1993). These references are only indicative and are by no means exhaustive or complete. The results of these and several more B-W studies have been reanalysed and summarised by Fernley (1994) and Fernley et al. (1998) who find a relation $M_V(RR) = 0.20 \pm 0.04[Fe/H] + 0.98 \pm 0.05$ between the absolute visual magnitude and the metallicity of the RR Lyrae stars. This result is intermediate but closer to the short distance scale, corresponding to $(m-M)_{LMC} \sim 18.34$.

The previous B-W analyses were based on: i) Kurucz (1979) model atmospheres, with turbulent velocity V_{turb} = 2 km/s; ii) semi-empirical temperature calibration; iii) mostly IR (i.e. K), but also visual V,R and I photometry; iv) the use of an average value for gravity (usually log$g$=2.75); v) a restricted phase range for fitting (usually 0.35 to 0.80); vi) the barycentric (also called γ-) velocity derived as simple integration over the entire pulsation cycle; vii) a constant factor (1.38) to transform radial into pulsational velocities.

Several model atmospheres are now available, with: improved *opacities*; different treatments of *convection*; different values of *turbulent velocity*; more accurate *temperature and BC calibrations*. The aim of the present work is to test what is the effect of these new models and calibrations, as well as of other assumptions, on the B-W results for RR Lyrae stars.

2. Our re-analysis: assumptions and approximations

2.1. New elements

• **Model atmospheres.** We have used the following sets of model atmospheres: i) Kurucz (1995) with MLT+overshooting treatment of convection, V_{turb} = 2 and 4 km/s, [m/H]=0.0; ii) Castelli (1999b) with MLT without overshooting treatment of convection, [m/H]=0.0 and V_{turb} = 2 km/s, and [m/H]=–1.5 and V_{turb} = 2 and 4 km/s. The models at [m/H]=–1.5 are enhanced in α-elements by $[\alpha/\alpha_{\odot}]$=+0.4. iii) Castelli (1999a) experimental models with no convection. These models do not have physical meaning, but are only intended to mimick the effects of recent treatments of convection, e.g. MLT with l/H=0.5 instead of 1.25 (Fuhrmann, Axer, & Gehren 1993), or Canuto & Mazzitelli (1992) approximation that predicts a very low convection or zero convection for stars with $T_{eff} \geq$ 7000 K and that has been suggested to provide a better match to the data (see Gardiner, Kupka, & Smalley 1999 for a recent re-discussion of this issue). The no-convection models are available for [m/H]=0.0 and –1.5 and V_{turb} = 2 km/s.

• **Gravities.** The values of log$g$ have been calculated at each phase-step from radius percentage variation (assuming ΔR/$< R > \sim$ 15%) plus the acceleration component derived from the radial velocity curve. The zero-point was set from theoretical ZAHB models, i.e. log$g$=2.86 at the phase corresponding to average radius. Note that all ZAHB models give average log$g$=2.86 ± 0.01 (Dorman, Rood, & O'Connell 1993; Sweigart 1997 with no He-mixing; Chieffi, Limongi

& Straniero 1998) with the only exception of Sweigart (1997) models with He-mix=0.10 which give log$g$=2.75 but may not be applicable to our field stars.
• **Semi-empirical Teff and BC calibration.** We have used Montegriffo et al. (1998) semi-empirical BC_V and BC_K calibration and temperature scale for PopII giants, that is based on RGB and HB stars in 10 globular clusters.
• **Gamma-velocity.** The default value of the γ-velocity was estimated from integration of the observed radial velocity curve over the entire pulsation cycle, as it was done in all previous B-W studies. However, Oke, Giver, & Searle (1962) had suggested for SU Dra that velocity gradients may exist in the atmosphere, and proposed to take them into account by correcting the observed radial velocities of a positive quantity that would vary about linearly between phase 0.95 and 0.40. On the other hand, Jones et al. (1987) found no observational evidence of velocity gradients among weak metal lines in X Ari, at least within their observational errors ($\pm$ 2 km/s). Chadid & Gillet (1998), however, did seem to find some evidence of differential velocities among weak metal lines in RR Lyr: the radial velocity curve from the FeII(λ4923.9) line shows a slightly larger amplitude than that from the FeI(λ4920.5) line which forms a little deeper in the atmosphere. A similar effect was found between BaII and TiII lines, and is related to the presence of strong shocks.
Therefore, in addition to the default γ-velocity calculation from the observed RV curve, we have simulated two other cases, γ-1 where the RV curve has been corrected as suggested by Oke et al. (1962) albeit by a much smaller amount (+ 2.0 km/s at most), and γ-2 where the amplitude of the RV curve has been stretched by $\pm$ 5 km/s at the phases of maximum and minimum RV. These simulations are only numerical experiments and do not intend to provide realistic answers to the problem of radial velocity gradients in the atmosphere: the radial velocities for the RR Lyrae stars are derived from a large number of weak metal lines and it is still totally unclear which correction (if any) should be applied to the average values in the presence of velocity gradients among some of these lines.

2.2. Old Assumptions

• **The p-factor.** The factor used to transform radial into pulsational velocity has been assumed to be 1.38, as in Fernley (1994). It might be a few % smaller, this conservative assumption gives the brightest possible luminosity as a function of p.
• **Fitting phase interval.** As with all previous applications of the B-W method, the fitting has not been performed on the entire pulsation cycle, but on a restricted phase interval appropriate for each star: 0.30-0.80 for SW And, for best stability of results; and 0.25-0.70 for RR Cet, to avoid shock-perturbed phases.

3. Results on SW And and RR Cet, and Discussion

3.1. SW And

We have used all possible and compatible data from the literature, i.e. BVRIK and uvby photometry, and radial velocities. The adopted input parameters

for this star are [Fe/H]=0.0, E(B–V)=0.09, γ-velocity=–19.94 km/s and $< V_0 >$=9.44.

The default model calibration on Vega led to systematically hotter temperatures (by $\sim$ 180K) from the (B–V) colors with respect to all other colors. This difference has no physical justification, and is only due to a behaviour of the models that was already known and commented by Castelli (1999b). It is worth mentioning that this hotter temperature by $\sim$ 180K leads to a brighter M_V magnitude by $\sim$0.12 mag using the combination V and B$-$V in the B-W analysis, and by only $\sim$0.02 mag using K and B$-$V. *It is important to note that the use of the K magnitude with any color, in particular V$-$K, is the least affected by temperature uncertainties, and provides the most stable results.*

In Table 1 we summarize the values of M_V that result from the use of the K magnitude and the various colors and models. The models are labelled as: K2 and K4 for Kurucz (1995) with V_{turb}= 2 and 4 km/s respectively; K2-nover and K2-noconv for Castelli (1999a,b) V_{turb}= 2 km/s and the no-overshooting and no-convection approximations respectively; Montegriffo for the Montegriffo et al. (1998) temperature scale and BC_K calibration.

Table 1. Determinations of M_V for SW And

Model	b$-$y	B$-$V	V$-$R	V$-$I	**V$-$K**	R$-$K
K2	1.11	0.83	1.02	1.07	**0.93**	0.97
K4	1.09	0.91	1.03	1.05	**0.92**	0.95
K2-nover	1.08	0.84	0.93	0.99	**0.96**	0.97
K2-noconv	0.62	0.40	0.46	0.51	**0.48**	0.49
Montegriffo					**0.94**	

We note that:

- The use of the b$-$y colors yields unreliable results because the angular diameter curve is distorted and the fitting to the linear radius curve is poor.
- The no-convection models yield much brighter magnitudes, the exact amount of "brightening" depending on the details of the convection treatment.
- All models, except the no-convection ones, yield consistent results with the empirical relation by Montegriffo et al. (1998).
- The present results, except the no-convection ones, are consistent with the previous determination of M_V for SW And, i.e. **0.94** (Fernley 1994).

3.2. RR Cet

We have used all compatible BVRIK photometry and radial velocities from the literature. The adopted input parameters for this star are [Fe/H]=–1.5, E(B–V)=0.05, γ-velocity=–74.46 km/s and $< V_0 >$=9.59.

The default model calibration on Vega for the [Fe/H]=–1.5 models led to consistent temperatures within $\sim$ 100K from all colors.

In Table 2 we summarize the values of M_V for RR Cet that result from the use of the K magnitude and the various colors and models. In addition to the models described also in Table 1, we have here a few other cases: K4-nover for

Castelli (1999b) V_{turb}= 4 km/s and the no-overshooting approximation; K2/K4-nover for V_{turb} = 4 km/s only at phases 0.60-1.00 and V_{turb} = 2 km/s elsewhere; γ-1 for a corrected RV curve by + 2 km/s at the phase of minimum RV; γ-2 for a corrected RV curve whose amplitude has been stretched by ± 5 km/s.

Table 2. Determinations of M_V for RR Cet

Model	B−V	V−R	V−I	**V−K**	R−K
K2-nover	0.54	0.44	0.47	**0.57**	0.60
K2-noconv	0.53	0.42	0.45	**0.55**	0.59
K4-nover	0.51	0.41	0.45	**0.55**	0.59
K2/K4-nover	0.64	0.48	0.51	**0.58**	0.60
K4-nover γ-1	0.54	0.44	0.48	**0.58**	0.61
K4-nover γ-2	0.35	0.25	0.30	**0.39**	0.43
Montegriffo	0.48			**0.56**	

We note that:

• The no-convection models seem to have no significant effect on the derived magnitudes.

• The use of V_{turb} = 4 km/s all over the fitting phase interval yields insignificantly brighter magnitudes (by ≤ 0.03 mag) with respect to the case at V_{turb} = 2 km/s. On the other hand, setting V_{turb} = 4 km/s only at phases 0.60-1.00 and V_{turb} = 2 km/s elsewhere leads to somewhat fainter magnitudes, the effect being stronger in the bluer colors.

• Correcting the RV curve as suggested by Oke et al. (1962) by at most + 2 km/s at the phase of minimum RV (case γ-1) leads to slightly fainter magnitudes.

• Correcting the RV curve by stretching the amplitude in analogy to the behaviour of FeII and BaII lines (case γ-2) leads to brighter magnitudes. The amount of brightening we have estimated is however too large, since the correction we have applied (± 5 km/s) was exaggerated for the sake of computation.

• All models yield consistent results with the empirical relation by Montegriffo et al. (1998).

• The present results are slightly brighter than the previous determination of M_V for RR Cet, i.e. **0.68** (Fernley 1994).

3.3. Conclusions

• The meaning of our simulations with the no-convection models is only to point out that, if the effect of convection were indeed overestimated by the present MLT, a more correct treatment with a reduced impact of convection would lead to brighter magnitudes for solar-metallicity stars, but would have lesser consequences on metal-poor stars. However, Gardiner et al. (1999) reach no definitive conclusion on this subject, and suggest that the classical treatment of convection with l/H=1.25 may still be the best approach in the temperature range 6000-7000K which is relevant for RR Lyrae stars around minimum light.

• The corrections to the radial velocity curves simulated with RR Cet are quite arbitrary and not sufficiently supported by observational evidence. They are

only intended as numerical experiments to test their effect on the derived magnitudes.

• The present results are quite compatible with the results from previous analyses, and do not support a significantly brighter zero-point for the RR Lyraes luminosity scale.

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